Future climate change spells catastrophe for Blanchard's cricket frog, *Acris blanchardi* (Amphibia: Anura: Hylidae)

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Abstract. Climate change may be one of the greatest environmental catastrophes encountered by modern human civilization. The potential influence of this global disaster on wildlife populations is subject to question. I interpolated how seasonal variation in weather patterns influences growth and reproduction in the Blanchard's cricket frog (*Acris blanchardi*). Then I extrapolated the influence of future climate conditions on these life history characteristics using fuzzy regression. Fuzzy regression was an accurate predictor of growth and reproduction based on the climate conditions present from 1900–2007. It predicted that the climate projections expected for Arkansas by 2100 could reduce total reproductive investment in the Blanchard's cricket frog by 33–94%. If these results reflect responses by other poikilotherms, climate change could induce major population declines in many species. Because poikilotherms represent the vast majority of vertebrates and significant ecosystem components, it is imperative that we implement strategies to reduce greenhouse gas emissions and circumvent this possible catastrophe.

Key Words. *Acris blanchardi*, amphibians, climate change, fuzzy regression, global warming, growth, reproduction, reproductive investment

INTRODUCTION

The impending threat of climate change is a serious concern for the global scientific community (Opdam and Wascher, 2004; Travis, 2000). I am especially concerned about how amphibians respond to this stressor because current amphibian extinction rates are progressing so fast (Blaustein et al., 1994; McCallum, 2007; Roelants et al., 2007; Stuart et al., 2005; Wheeler et al. 2002). The potential causes of these declines are numerous and include habitat degradation and loss (Brooks et al., 2002), introduced species (Adams, 1999), pollution (Dunson et al., 1992), contaminants (Reeder et al., 1998; Relyea, 2005), pathogens (Berger et al., 1998; Daszak et al., 2002), climate change (Pounds and Crump,

1994; Pounds et al., 1999), or interactions among several factors (McCallum and Trauth, 2003; Pounds et al., 2006; Trauth et al., 2006).

Alteration of precipitation patterns due to climate change may influence many aspects of the biology of an organism. It may partly explain the demise of the golden toad (Pounds et al., 1999) and may drive amphibian disease epidemics such as chytrids (Pounds et al., 2006). The warming climate may even reduce the intensity of sexual selection, especially by influencing call parameters (Gerhardt and Mudry, 1980; Sullivan, 1982; Cocroft and Ryan, 1995).

It can reduce the overall abundance in anurans (Piha et al., 2007). Climate associated drought can drive population fluctuations by selecting against specific age classes of rainforest frogs (Stewart, 1995) and certainly would positively or negatively influence temperate species as well. In the case of the golden toad and the harlequin frog, the humid climate needed for survival migrated above the mountain leaving no acceptable habitat for these species (Pounds et al., 1994). Interactions between the increased drought and agriculture-induced landscape homogenization may lead to catastrophic species declines (Piha et al., 2007). Unfortunately, the complex relationships among climate variables and other stressors (Gunn et al., 2004) make it difficult to study their influence on amphibian life history and declines (Blaustein and Kiesecker, 2002; Davidson et al., 2002).

We lack a firm understanding of the natural history for many amphibians (Bury, 2006; McCallum and McCallum, 2006; Trauth, 2006). Conservation biologists use the natural history of species as the backbone for orchestrating conservation programs and making management decisions (Bury, 2006; Greene, 2005; Wilcox and Possingham, 2002). This makes understanding how climate change may influence natural history characteristics of utmost importance as we plan necessary conservation responses (Stenseth and Mysterud, 2002; Winkler et al., 2002).

Growth and reproduction are two of the four primary aspects of natural history traits typically related to the health of an organism (the other two are development and behavior; Newman, 2001). Growth rate and duration play major roles in determining the ultimate body size (Werner, 1986) and reproductive output (Blueweiss et al., 1978) of an individual. Body size and growth are important metabolic determinants of an organism's overall competitive ability (Batzli et al., 1977; Blueweiss et al., 1978; Werner, 1986) and metabolism in poikilotherms is influenced by ambient temperature (Lofts, 1972). Generally, larger individuals have fewer predators (Werner, 1986; Rowe and Ludwig, 1991; Jung, 1995; Laurila and Kujasalo, 1999), can compete better for mates (Berven, 1981; Howard, 1998; Smith, 1987), and are more resistant of desiccation (Nevo, 1973a; Stewart, 1995; Wilmer et al., 2000). Larger females typically produce larger eggs and egg clutches (Darwin, 1874; Lofts, 1974; McCallum, 2003), although there are exceptions (Shine, 1988). Therefore, stressors that suppress growth can affect reproduction and survivorship (Batzli et al., 1977; Fraser and Gilliam, 1992).

The systematics of Blanchard's cricket frog has been the subject of much debate (McCallum, 2006; Rose et al., 2006; Gamble et al., 2008). These frogs frequently occur along stream banks and around springs (Trauth et al. 2004), where they are known for their seemingly haphazard jumping patterns when escaping pursuers (McCallum, 1999). Blanchard's cricket frog hibernates terrestrially under rocks in Arkansas (McCallum and Trauth, 2003b), Oklahoma (Blair, 1951), Louisiana (Walker, 1963), and in cracks in the

soil in Illinois (Gray, 1971). They have a low tolerance for inundation while hibernating (Irwin and Lee, 1999) and they often die when forced to hibernate in an aquatic laboratory setting (McCallum and Trauth, 2003b). Calling behavior and immune function are closely tied to temperature (McCallum and Trauth, 2007), and we could not maintain these frogs in reproductive condition without orchestrating a combination of cool water and hot air temperatures (McCallum, 2003). They rapidly succumb in captivity to eutrophication arising from warm water (pers. observ.). Males often call from inside clusters of emergent grasses near oviposition sites (pers. observ.). Oviposition typically occurs in heavily vegetated (e.g., *Myriophyllum* sp., *Ceratophyllum* sp., and algal mats comprised of *Spirogyra* sp. and *Lemna* sp.), shallow water habitats (Regan, 1972; McCallum, unpubl. data) that provide ideal habitat for their larvae (Johnson 1988). In Arkansas, metamorphs emerge from these habitats starting in early July and extending through early winter (McCallum, 2003). They disperse along stream banks and riparian areas, generally avoiding adults possibly due to cannibalism (McCallum et al., 2001). Froglets feed on various insects, especially *Collembola* (Johnson and Christiansen, 1976), with the size of prey generally increasing with body size to encompass small Hymenoptera and Orthoptera (McCallum, unpubl. data). There is a report of attempted cannibalism by adults on metamorphs (McCallum et al., 2001).

Body size of Blanchard's cricket frog (*Acris blanchardi*) varies geographically with precipitation levels (Nevo, 1973b). Males and females reach a minimum adult size in about two months after metamorphosis, but continue to grow until they die, usually within one year post-metamorphosis (McCallum, 2003). Males begin calling in early summer, with gravid females entering the chorus largely from late May through June. By September, juveniles of near adult size dominate the population and adults from the previous breeding season are seldom encountered (McCallum, 2003).

Because the biology of Blanchard's cricket frog is tied to temperature, and its body size correlates regionally with precipitation, and temperature-precipitation regimes influence the biology of other poikilotherms (Kristensen et al., 2006; McCallum et al., 2009), I asked if climate change-induced temperature and precipitation flux may influence the growth rates and resulting body sizes of this frog. I report how Blanchard's cricket frog (*A. blanchardi*), may respond to these predicted changes in temperature and precipitation. I hypothesized that annual changes in seasonal rainfall and temperature may influence growth and reproduction in the *A. blanchardi* leading to future changes in growth and reproduction. If this were true, I could model interpolated growth and climate data with regression techniques ($\alpha = 0.05$), and then extrapolate the influence of projected climate change on growth and reproduction using fuzzy regression techniques. If no relationship existed, then no dependable models should be identified, making extrapolation impossible.

MATERIALS AND METHODS

Fuzzy mathematics is a conservative, non-subjective generalization of interval analysis that is used for dealing with uncertainty, and requires fewer data than alternative methods like Monte Carlo simulations (Silvert, 1997, 2000; Ferson et al., 1999). This method is useful with all kinds of uncertainty, and the subjective interpretations characteristic of Monte Carlo approaches are unneed-

ed. It is based on a consistent axiomatic system that is different from that used in probability theory (Ferson et al., 1999). Fuzzy mathematics rates data (x-axis) based on degrees of possibility called membership values (y-axis) where y = 0 = lowest possibility and y = 1= highest possibility. If the graphical representation is a triangle, then only one value has the membership value y = 1. If the representation is a trapezoid, then a series of values across the top of the polygon are equally possible and all have membership values y = 1. All other x-values have decreasing membership values (i.e., possibilities) as y approaches zero. Fuzzy mathematics is particularly useful where high levels of uncertainty such as ambiguity, non-specificity, discord, and fuzziness exist (Klir and Yuan 1994). Extrapolation of future events is difficult to interpret and plagued by uncertainty. Fuzzy mathematics is specifically useful for dealing with this kind of uncertainty and the associated questionable data sets (Silvert, 1997, 2000; Ferson et al., 1999), making it well suited for analyzing the effects of future climate change on the life history of an organism.

I interpolated climate patterns (National Oceanic and Atmospheric Association [NOAA], 2000) with reproduction and growth data from *A. crepitans* (Table 1; McCallum, 2003) using multiple and best subsets regression (Neter et al., 1996). I used seasonal average temperatures and levels of precipitation because seasonal timing of climate events may be more important than annual variation (Arak, 1983; McCallum et al., 2009). Then I used fuzzy regression techniques where the variables were fuzzy (Taheri, 2003) with previously reported climate change scenarios (U.S. EPA, 1998) to extrapolate growth and reproductive outcomes. I constructed fuzzy numbers using the maximum, minimum, and best predictions of climate change in Arkansas by 2100 (Table 1; U.S. EPA, 1998). I substituted fuzzy numbers for the variables in the predictive regression models, then I combined the regression models using substitution to construct more complex regression models that predicted the snout-vent length (SVL), body mass (BM), body condition score (BCS), ovarian length (OL), number of mature ova (MO), maximum ova diameter (OD), egg volume (EV), and total investment

Table 1. Average seasonal temperature (ºC) and precipitation (cm) data observed from 1901 – 2007 (NOAA, 2000), predicted due to climate change by 2100 (U.S. EPA 1998), and the associated fuzzy numbers. The mean/best column refers to the average from 1901-2007 or the best estimate from the United Kingdom Hadley Center's Climate Model (HadCM2).

	Low	Mean/Best	High	Fuzzy Number
Mean Winter Temperature 1901-2007	1.28	5.42	9.11	[1.28, 5.42, 9.11]
Mean Spring Temperature 1901-2006	13.60	15.74	17.61	[13.60, 15.74, 17.61]
Mean Summer Temperature 1901-2006	24.28	26.04	26.33	[24.28, 26.04, 26.33]
Mean Fall Temperature 1901-2006	13.50	19.34	19.56	[13.50, 19.34, 19.56]
Mean Winter Precipitation 1901-2007	10.26	30.86	58.62	[10.26, 30.86, 58.62]
Mean Spring Precipitation 1901-2006	6.21	14.90	26.83	[6.21, 14.90, 26.83]
Mean Summer Precipitation 1901-2006	10.64	28.07	44.78	[10.64, 28.07, 44.78]
Mean Fall Precipitation 1901-2006	11.61	28.75	58.65	[11.61, 28.75, 58.65]
Predicted Winter Temperature 2100	5.97	6.01	8.74	[5.97, 6.01, 8.74]
Predicted Spring Temperature 2100	16.32	17.43	18.54	[16.32, 17.43, 18.54]
Predicted Summer Temperature 2100	26.60	27.15	29.37	[26.60, 27.15, 29.37]
Predicted Fall Temperature 2100	17.14	18.25	19.36	[17.14, 18.25, 19.36]
Predicted Winter Precipitation 2100	10.26	30.86	58.62	[10.26, 30.86, 58.62]
Predicted Spring Precipitation 2100	39.58	43.35	47.12	[39.58, 43.35, 47.12]
Predicted Summer Precipitation 2100	30.73	34.93	39.12	[30.73, 34.93, 39.12]
Predicted Fall Precipitation 2100	30.38	33.27	36.16	[30.38, 33.27, 36.16]

in reproduction (TI). I validated these models by comparing observed reproductive and growth data to the average values that were derived from fuzzy regressions using weather data from 1901-2007. Then I compared the modeled results from 1901-2007 to the extrapolated results for 2100 to infer the risk of climate change to reproduction in *A. blanchardi*.

<div align="center">RESULTS</div>

Interpolation of climate effects on growth and reproduction resulted in equations 9 – 11 (Table 2). Many of the equations predicted intervals for life history traits resembled previously reported values (McCallum, 2003). For example, fuzzy climate variables gave accurate fuzzy intervals for SVL and BM. BCS was a better predictor of OL than was SVL, although SVL provided accurate results for the number of MO. BCS and OL that was derived from the BCS (OL$_{BCS}$) gave similar outputs and reflected previous reports for the diameter of the OD (McCallum, 2003). Ovarian length that was derived from SVL (OL$_{SVL}$) was not a good

Table 2. Regression models for growth and reproductive traits in the Northern Cricket Frog (*Acris crepitans*). Key: BM = body mass (g), SVL = Snout-vent length (mm), BCS = body condition score, OL = ovarian length (mm), LO = largest ova diameter (μm), MF = mature follicles (n), VF = vitellogenic follicles (n), WT = winter temperature (ºC), SPT = spring temperature (ºC), FR = fall rain (cm), SPR = spring rain (cm), SUR = summer rain (cm), WR = winter rain (cm).

1. SVL$_{♀}$ vs. OL (r^2 = 0.200, df = 3, 57, P = 0.005):
OL = 30.8410 – 4.11180 SVL + 0.198410 SVL^2 – 0.0028678 SVL^3

2. BCS$_{♀}$ vs. OL (r^2 = 0.156, df = 1, 45, P = 0.006):
OL = 2.40320 + 77.6546 BCS

3. BCS$_{♀}$ vs. LO (r^2 = 0.311, df = 1, 45, P < 0.001)
LO = -179.298 + 14024.0 BCS

4. OL vs. LO (r^2 = 0.612, df = 2, 62, P < 0.001):
LO = -420.728 + 190.576 OL – 5.15409 OL^2

5. SVL$_{♀}$ vs. MF (r^2 = 0.273, df = 3, 28, P = 0.028):
MF = (1253.58 – 147.312 SVL + 5.5347 SVL^2 – 0.0568778 SVL^3) (2 ovaries)

6. SVL$_{♀}$ vs. VO (r^2 = 0.231, df = 31, P = 0.022):
VO = 632.575 – 47.9119 SVL + 1.22306 SVL^2

7. BM$_{♀}$ (r^2 = .840, P < 0.001):
BM = 0.193950 – 0.0449324 SVL + 0.0029810 SVL^2 + 0.0000419 SVL^3

8. BM$_{♂}$ (r^2 = 0.771, P < 0.001):
BM = 0.560328 + 0.0213750 SVL + 0.0024595 SVL^2

9. SVL$_{♀}$ vs. WT, SPT, SUR, and SPR (r^2 = 0.031, df = 4, 1386, P < 0.001:
SVL = 33.1 - 0.835 WT – 0.626 SPT + 0.0453 SUR – 0.0334 SPR

10. BCS$_{♀}$ vs. WT, FR, WR, SPR (r^2 = 0.049, df = 4, 1386, P < 0.001:
BCS = 0.0850 – 0.00431 (WT) – 0.000298 (FR) + 0.000224 (WR) – 0.000194 (SPR).

11. BM$_{♀}$ vs WT, FR, WR, SPR (r^2 = 0.035, df = 4, 1386, P < 0.001:
BM = 2.00 – 0.109 (WT) – 0.00648 (FR) + 0.0565 (WR) – 0.00604 (SPR)

Table 3. Fuzzy estimates of life history characteristics under the climate observed from 1901-2007 and predicted changes by 2100. Numbers in brackets are fuzzy estimates representing the vertices of their triangular or trapezoidal shape. Percentages in parentheses are the percentage change in the statistic with a membership value = 1. MV_0 is the membership value when the life history trait = 0.

Life History Trait	McCallum 2003	Calculated 1901-2007	Predicted 2100	% Change
SVL$_\female$ (mm)	21.53 SD = 1.87	[14.06, 19.49, 25.34]	[14.015, 17.30, 18.35]	[-44.69, -11.23, 30.55]
BM$_\female$ (g)	1.71 SD = 0.74	[1.04, 2.88, 5.06]	[2.27, 2.61, 2.66]	[-55.10, -9.23, 154.36]
BCS$_\female$	0.051 SD = 0.29	[0.025, 0.057, 0.088]	[0.034, 0.0468, 0.0476, 0.495]	[-60.97, -16.48, 1850.6]
OL using SVL (mm)	5.86 mm SD = 2.0	[-80.79, 4.84, 92.46]	[-23.35, 4.24, 32.12]	$MV_0 > 0.9$, (-12.4%)
OL using BCS (mm)	5.86 mm SD = 2.0	[4.37, 6.84, 9.23]	[5.07, 6.11, 40.80]	[-45.10, -10.69, 833.3]
LO using BCS (μm)	480.9 SD = 277.9	[176.23, 621.39, 1054.11]	[302.1, 489.442, 489.445, 6755.8]	[-71.3, -21.2, -21.2, 3734]
LO using OL$_{SVL}$ (μm)	480.9 SD = 277.9	[-59879, 380.92, 17199.9]	[-10189.25, 294.83, 5700.98]	$MV_0 > 0.9$, (-12.4%)
LO using OL$_{BCS}$ (μm)	480.9 SD = 277.9	[-27.00, 641.67, 1239.86]	[-8036.31, 550.79, 550.80, 7223.20]	$MV_0 > 0.9$, (-22.6%)
Average LO (μm)	480.9 SD = 277.9	[-19909.93,547.99,6497.96]	{-5974,445,6560]	$MV_0 > 0.9$, (-18.8%)
MF	157, SD = 17.87	[-4622,128,5156]	[-1428,134,1792]	$MV_0 > 0.9$, (+4.5%)
EV$_{BCS}$ (μm³)	--	[2.29e7, 1.01e9, 4.91e9]	[1.44 e7, 6.14 e7, 1.61 e11]	[-99.7, -93.9, 7030]
EV$_{OLSVL}$ (μm³)	--	[-1.12e14, 2.89e7, 2.66e12]	[-5.54e11, 1.34e7, 9.70e10]	$MV_0 > 0.9$, (-53.6%)
EV$_{OLBCS}$ (μm³)	--	[1.03e4, 1.38e8, 9.98e8]	[-2.72e11, 8.75e7, 1.97e11]	$MV_0 > 0.9$, (-36.6%)
TI$_{BCS}$ (μm³)	--	[-2.27e13, 1.29e11, 2.53e13]	[-2.3e14, 8.23e09, 2.89e14]	$MV_0 > 0.9$, (-93.6%)
TI$_{OLSVL}$ (μm³)	--	[-5.77e17, 3.70e09, 5.18e17]	[-9.93e14, 1.80e09, 7.91e14]	$MV_0 > 0.9$, (-51.4%)
TI$_{OLBCS}$ (μm³)	--	[-4.61e12,1.77e10,5.15e12]	[-4.87e14, 1.17e10, 3.88e14]	$MV_0 > 0.9$, (-33.9%)

predictor of OD. Some of the fuzzy regression results gave large intervals, but x-values with high membership values (Y > 0.5) resembled previous reports (McCallum 2003).

These data predict reduced SVL, BM, BCS, OL, and OD by 2100; whereas, they predict increased MO relative to 1901-2007 predictions (Table 3). This culminated in a large reduction in EV (36-94% drop) and ultimately, TI (37-94% drop; Table 3). MO, EV, and TI had high membership values greater than 0.9 for X = 0. Any time X < 0, it was considered to be biologically zero because no investment existed in that trait.

DISCUSSION

The fuzzy regression produced fuzzy intervals for 1901-2007, which included values similar to actual observations (McCallum, 2003). That finding appears to validate the accuracy of the fuzzy regression approach for predicting climate effects on life history traits. This method provides us with greater confidence in the fuzzy regression forecasts (Heshmaty and Kandel, 1985) for future climate influences on these life history traits. Overall, it revealed that both growth and reproduction in this species could be severely hampered by prospective climate change scenarios.

Not surprisingly, BCS and OL_{BCS} provided similar predictions of OD. The small differences between these results may reflect differences in rounding between the calculations for each, or amplification of error in the OL_{BCS} results. The OL_{SVL} underestimated OD relative to actual observations and calculations obtained from BCS and OL_{BCS}. This is probably because egg size is generally related to both the body size and the amount of fat stores available for investment in ova (Lofts, 1974). The SVL tells little about the available fat stores, whereas individuals with sufficient resources for reproduction will generally have higher BCS values (Darwin, 1874; Lofts, 1974). Therefore, the variation between these predictors seems to follow conventional wisdom in that larger females have larger ovaries, hence greater numbers of larger ova (Zera and Harshman, 2001).

Although most life history traits decreased under the predicted changes in Arkansas climate, MO increased 4.5%. Generally, we expect larger females to produce more ova (Zera and Harshman, 2001). This trade-off between ova size and ova number may be adaptive under high stress conditions. Unfortunately, the small increase does not counterbalance the ultimately reduced reproductive investment experienced by frogs in 2100. The frogs are producing a few more eggs, but these are much smaller than ideal. Smaller egg size due to climate change is likely to reduce survivorship of larvae and ultimately recruitment (Zera and Harshman, 2001).

These results suggest future concern for populations of *A. crepitans*. These anurans are adapted to current climate conditions. I thought that increased precipitation would promote this species, but the complex interactions among seasonal perturbations in rainfall and ambient temperature may instead be detrimental. This is a critical point for those studying the influence of climate variables on life histories. Timing of climate patterns may be more important than the annual changes involved. Summer temperature was not a factor in any model. This may be because predicted increases in summer temperatures are unrelated to periods of dormancy in this species. Warmer spring or fall temperatures resulting from climate change would shorten the dormancy period as warmer tempera-

tures persist longer into the winter and ensue earlier in the spring. This could lengthen the period of activity for this species and/or increase the metabolic rate of the frogs that do not return from dormancy. This could reduce the BCS as they burn resources due to these periods of warm weather leading to increased metabolism without raised intake of food (Lofts, 1972). This could drain resources available for growth and reproduction during the following breeding season. Other kinds of stressors such as immune stress are known to similarly reduce reproduction and growth in male *A. crepitans* (McCallum and Trauth, 2007). Reduced reproduction and body growth can influence age-specific reproduction, survival rates, population growth rates, effective population sizes, and censused population sizes (Soule and Mills, 1998), and these factors can feed back on themselves (Gilpin and Soule, 1986) leading to an extinction vortex. (Mills, 2007). Therefore, my extrapolations provide evidence that future climate change could seriously impair this species, especially the already declining populations in the northern parts of its range (Lehtinen and Skinner, 2006).

On a broader scale, the results of this study draw concern about the potential for climate change to similarly impact poikilothermic vertebrates, potentially driving them to extinction. Amphibians, reptiles, and fishes represent most of the vertebrate species on the planet (Wilson, 1992) and are responsible for significant ecosystem services (Balvanera et al., 2001; Schlaepfer et al., 1999; Myers, 1996), form the prey base for many other organisms (Blaustein and Kiesecker, 2002.), and provide population control of many pest organisms (Hirai and Matsui, 1999) including vectors of serious human diseases (Durvasula et al., 1997). Most of these organisms have poor dispersal ability (Gibbs, 2004; Bohonak, 1999) are unlikely to migrate with moving climates during a mere century, and their physiology is tightly tied to temperature (McCallum and Trauth, 2007), thereby amplifying effects of local climate change on life history traits. For this reason, pre-emptive strategies that aim for elimination of greenhouse gasses remain both the best and imperative courses of action for the conservation of amphibians and similar poikilotherms.

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